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Hope and Inquietudes in Nucleo-cosmochronology

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Abstract. Critical views are presented on some nucleo-cosmochronological questions. Progress has been made recently in the development of the ^{187}Re-^{187}Os cosmochronometry. From this, there is good hope for this clock to become of the highest quality for the nuclear dating of the Universe. The *simultaneous* observation of Th and U in ultra-metal-poor stars would also be a most interesting prospect. In contrast, a serious inquietude is expressed about the reliability of the chronometric attempts based on the classical ^{232}Th-^{238}U and ^{235}U-^{238}U pairs, as well as on the Th (without U) abundance determinations in ultra-metal poor stars.

1. Introduction

The use of radionuclides to estimate astrophysical ages has a long history, a milestone of which is the much celebrated piece of work of Fowler & Hoyle (1960). For long, the field of nucleo-cosmochronology that has emerged from this paper has been aiming at the determination of the age $T_{\rm nuc}$ of the nuclides from abundances in the material making up the bulk of the solar system. If indeed the composition of this material witnesses the long history of the compositional evolution of the Galaxy prior to the isolation of the solar material, a reliable evaluation of $T_{\rm nuc}$ (clearly a lower bound to the age of the Universe) requires (i) the identification of radionuclides with half-lives commensurable with estimated reasonable galactic ages (i.e. $t_{1/2} \gtrsim 10^9$ y), (ii) the construction of nucleosynthesis models that are able to provide the isotopic or elemental yields for these radionuclides, (iii) high quality data for the meteoritic abundances of the relevant nuclides, and, last but not least, (iv) the build-up of models for the evolution of the abundances of these nuclides in the Galaxy, primarily in the solar neighborhood. All these requirements clearly make the chronometric task especially demanding. While everybody would agree this far, there are different ways to look at the question.

A pessimistic view is that nucleo-cosmochronology can at best set limits on $T_{\rm nuc}$ through the use of a so-called 'model-independent' approach. Using this formalism, Meyer & Schramm (1986) conclude that $9 \lesssim T_{\rm nuc}({\rm Gy}) \lesssim 27$ (only the lower limit is truly model-independent. The upper limit depends on some model assumptions). This is clearly not a highly constraining range! An optimistic view is that, given the presumed complexity of the chemical evolution of the galactic disk, it is by far preferable to describe its nucleosynthetic history by a simple function with some adjustable parameters. This has been advocated by Fowler

over the years with the use of the so-called 'exponential model'. A practitioner's view is that it is really worth studying nucleo-cosmochronology in the framework of chemical evolution models which are simple enough not to account for all the dynamical aspects of the formation of the present galactic disk, but which imperatively satisfy as many observational constraints as possible [e.g. Yokoi et al. (1983), Takahashi (1998)].

A new chapter in the story of nucleo-cosmochronology has been written with the discovery of isotopic anomalies attributed to the *in situ* decay in a minute fraction of the meteoritic material of radionuclides with half-lives in the approximate $10^5 \lesssim t_{1/2} \lesssim 10^8$ y range. These observations are hoped to provide some information on discrete nucleosynthesis events that presumably contaminated the solar system at times between about 10^5 and 10^8 y prior to the isolation of the solar material from the general galactic material. Constraints on the chronology of nebular and planetary events in the early solar system could be gained concomitantly.

Finally, the observation of Th in some very metal-poor stars and of U in one of them has opened the way to a possible nuclear-based evaluation of the age of individual stars other than the Sun. This clearly broadens the original scope of nucleo-cosmochronology still further.

In Sect. 2, we reiterate the inquietude originally expressed by Yokoi et al. (1983) concerning the classical ^{232}Th-^{238}U and ^{235}U-^{238}U pairs, which may not be as reliable galactic clocks as it is often stated. In contrast, we express some hope concerning ^{187}Re-^{187}Os in Sect. 3. Our second inquietude relates to the chronological information one may really hope to gain from the observation of Th in very low-metallicity stars (Sect. 4). The situation would be brighter if one could rely on precise measurements of the Th/U ratio in such stars (Sect. 5). The chronometry using short-lived radionuclides is not discussed here. The interested reader is referred to e.g. Arnould et al. (2000) for a brief review of this question and references (see also T. Lee, these proceedings).

2. Inquietude 1: The trans-actinide clocks

The most familiar long-lived ^{232}Th-^{238}U and ^{235}U-^{238}U clocks based on the present meteoritic content of these nuclides are reviewed by J.W. Truran (these Proceedings). At several occasions, we have expressed reservations about the use of these pairs as reliable evaluators of $T_{\rm nuc}$ [e.g. Arnould & Takahashi (1990)].

The first reason for this inquietude relates to the clear necessity of knowing with high precision the production ratios of the involved actinides. Such quality predictions are clearly out of reach at the present time. One is indeed dealing with nuclides that can be produced by the r-process only, which suffers from very many astrophysics and nuclear physics problems, as we have emphasized at many occasions [e.g. Arnould & Takahashi 1999; Goriely & Clerbaux (1999)]. In particular, the true astrophysical site(s) of the r-process remain(s) so far unknown, preventing any firm (sometimes far-reaching) conclusions to be drawn in relation with nucleosynthesis applications. On the nuclear physics side, the nuclear properties (such as nuclear masses, deformations, ...) of thousands of exotic nuclei located between the valley of β-stability and the neutron drip line have to be known, as well as their transmutation rates through α- or β-decay,

various fission channels, as well as through nuclear reactions, such as (n,γ) and (γ,n). Despite much recent experimental effort, none of these quantities are known for the nuclei involved in the r-process, so that they have to be extracted from theory. In addition, the Th and U nuclides are the only naturally-occurring ones beyond ^{209}Bi, so that any extrapolation relying on semi-empirical analyses and fits of the solar r-process abundance curve is in danger of being especially unreliable.

Recent r-process calculations (Goriely & Clerbaux 1999) provide production ratios in the $0.8 \lesssim P_{235}/P_{238} \lesssim 1.2$ and $1.4 \lesssim P_{232}/P_{238} \lesssim 2.7$. The extent of these ranges largely forbids the build-up of precise nucleo-cosmochronometries. It has to be noticed that this problem would linger even if a realistic r-process model were given.

A second source of worry relates to the necessity of introducing nucleo-cosmochronology in chemical evolution models of the Galaxy that satisfy at best as many astronomical observables as possible, and to carefully check the internal consistency of such extended chemical models. In fact, this step is a quite complex one. Even if the nucleosynthesis yields of the radionuclides of relevance are assumed to be reliably known for all stellar masses and metallicities, which is far from being the case in reality, one still has to worry about such effects as the so-called 'astration', that is the possible more or less substantial destruction during the stellar lifetime of those nuclei which were absorbed from the interstellar medium at the stellar birth. From their constrained one-zone model for the evolution of the composition of the galactic disk in the solar neighborhood, Yokoi et al. (1983) conclude that (i) the predicted $(^{235}\mathrm{U}/^{238}\mathrm{U})_0$ and $(^{232}\mathrm{Th}/^{238}\mathrm{U})_0$ ratios at the time $T_\odot$ of isolation of the solar system material from the galactic one about 4.6 Gy ago (here and in the following, the subscript 0 refers to this time) is only very weakly dependent on galactic ages, at least in the explored range from about 11 to 15 Gy. This is analyzed as resulting largely from the expected rather weak time dependence of the stellar birthrate (except possibly at early galactic epochs, but a reliable information on these times is largely erased by the subsequent long period of chemical evolution), and (ii) the predicted abundance ratios at $T_\odot$ are consistent with those derived at the same time from meteoritic analyses if the r-process production ratios lie in the approximate ranges $1 < P_{235}/P_{238} < 1.5$ and $1.7 < P_{232}/P_{238} < 2$. The latter values are consistent with the predicted ones reported above, the former ones being only marginally so. At this point, it has not to be forgotten that the estimate of the level of convergence between predicted production ratios and observed abundances is blurred not only by the large uncertainties in the estimated r-process actinide yields, but also by the still quite large uncertainties affecting the meteoritic Th and U abundances, which amount to at least 25% and 8%, respectively (Grevesse et al. 1996).

Finally, let us remind that most of the huge amount of work devoted to the trans-actinide chronometries (e.g. J.W. Truran, these Proceedings) relies on the simple exponential model whose substantial mathematical ease is obtained at the expense of a quite scanty astrophysical content. This situation makes the use of the Th-U chronologies especially unreliable. As examplified by Arnould & Takahashi (1990), a given exponential model may predict an increase by a

factor of 3 in the $T_{\rm nuc}$ value by just changing the meteoritic $(^{232}{\rm Th}/^{238}{\rm U})_0$ ratio from 2.32 to 2.67, which is compatible with existing data (Grevesse et al. 1996)!

From the above considerations, one may restate the conclusion already drawn by Yokoi et al. (1983) that the relatively large uncertainties in the measured solar $(^{232}{\rm Th}/^{238}{\rm U})_0$ and $(^{235}{\rm U}/^{238}{\rm U})_0$ ratios coupled with the relatively weak dependence with galactic ages of these calculated ratios make it next to impossible to obtain a *reliable* value of $T_{\rm nuc}$ from the trans-actinide chronometries as they stand now. This conclusion holds even in the most favorable situation where the r-process predictions can be made compatible with the abundance measurements in the framework of a given model for the chemical evolution of the Galaxy. One has to be aware of the fact that there is no guaranty at this time to reach this necessary compatibility in a 'natural' way, i.e. without having to play around with a rich variety of parameters.

3. Hope 1: The ^{187}Re - ^{187}Os chronometry

First introduced by Clayton (1964), the chronometry using the ^{187}Re - ^{187}Os pair is able to avoid the difficulties related to the r-process modelling. True, ^{187}Re is an r-nuclide. However, ^{187}Os is not produced directly by the r-process, but indirectly via the β^--decay of ^{187}Re ($t_{1/2} \approx 42$ Gy) over the galactic lifetime. This makes it in principle possible to derive a lower bound for $T_{\rm nuc}$ from the mother-daughter abundance ratio, provided that the 'cosmogenic' ^{187}Os component is deduced from the solar abundance by subtracting its s-process contribution. This chronometry is thus in the first instance reduced to a question concerning the s-process. This is a good news, as the s-process is, generally speaking, better under nuclear or astrophysics control than the r-process. Other good news come from the recent progress made in the measurement of the abundances of the concerned nuclides in meteorites, which provide in addition the decay constant of the neutral ^{187}Re atoms. The derived value $\lambda = (1.666 \pm 0.010)^{-11}$ y^{-1} is substantially more precise than its direct determination (Faestermann 1998). This improved input is essential for the establishment of a reliable chronometry.

Even if the s-process models are by far in much better shape than the r-process ones, the evaluation of the relative production of ^{186}Os and of ^{187}Os by the s-process is not a trivial matter. One difficulty relates to the fact that the ^{187}Os 9.75 keV excited state can contribute significantly to the stellar neutron-capture rate because of its thermal population in s-process conditions ($T \gtrsim 10^8$ K). The ground-state capture rate measured in the laboratory has thus to be modified. Several estimates of this correction factor F_σ based on preliminary experimental data analyzed in the framework of Hauser-Feshbach models are available [e.g. McEllistrem et al. (1989)]. The question has been re-examined with the code MOST (Goriely 1998). In particular, the impact on the predictions of uncertainties in various key ingredients of the model (like the Γ_γ-width or the neutron optical potential) has been analyzed (Goriely, unpublished). There is also reasonable hope to reduce the uncertainty on F_σ through further dedicated experiments (Koehler and Mengoni, private communications).

A second difficulty has to do with the possible branchings of the s-process path in the $184 \leq A \leq 188$ region which may affect the evaluated $^{187}{\rm Os}/^{186}{\rm Os}$ s-process production ratio (Arnould et al. 1984). The modelling of these branch-

ings has been improved substantially with the measurements of radiative neutron capture cross sections in the mass range of relevance (Käppeler et al. 1991), as well as thanks to detailed s-process calculations in realistic model stars. We note in particular that estimate in the framework of the proton-mixing scenario of thermally pulsing AGB stars (Goriely & Mowlavi 2000) predict branching effects up to 20% on the ^{187}Os/^{186}Os ratio.

The development of the Re - Os chronology also needs a reliable estimate of the ^{187}Os and ^{187}Re yields from stars in a wide range of masses and metallicities. This evaluation requires not only a good-quality modeling of the s-process in order to predict the ^{186}Os/^{187}Os ratio, but also of other ^{187}Os and ^{187}Re transmutation channels in stellar interiors which may affect the ^{187}Re/^{187}Os ratio ('astration' effects). One of these mechanisms is the possibility of enhanced ^{187}Re β-decay in stellar interiors. This is especially the result of the bound-state β-decay phenomenon which has the dramatic effect of reducing the ^{187}Re half-life from about 42 Gy when one is dealing with a neutral atom to a mere 32.9 ± 2.0 y when complete ionization is obtained. The experiment that has allowed the measurement of this half-life (Bosch 1996) is a significant step forward in the establishment of a reliable Re - Os chronometry. It also put on safer grounds the evaluation of the rate of transformation of ^{187}Os into ^{187}Re that can occur in certain stellar layers through continuum electron captures (Arnould 1972, Takahashi & Yokoi 1983). A further complication arising in the evaluation of the astration effects comes from the fact that neutron captures can modify the ^{187}Re/^{187}Os ratio as well (Yokoi et al. 1983).

Clearly, the yield evaluation also requires the modelling of a variety of stars with different masses and metallicities. Model stars adopted in recent studies of the Re - Os chronology are briefly described by Takahashi (1998). The relevant yields can also be found in his work.

Last but not least, it remains to construct a model for the chemical evolution of the matter from which the solar system formed. This is the hardest part of all, even in the framework of the simple constrained models already referred to above. In their update of the study of Yokoi et al. (1983), Takahashi (1998) concludes that the ^{187}Re - ^{187}Os pair leads to $T_{\rm nuc}$ values in the reasonable 15 ± 4 Gy range.

This result may not be as impressive as one may wish. However, there is good hope that the Re - Os chronometry will turn well. Since the work of Yokoi et al. (1983), much progress has been made on the nuclear physics and meteoritic sides, and there is likely much more to come. This optimistic note cannot be expressed for the trans-actinide clocks (Sect. 2). Of course, more sophisticated galactic evolution models have to be devised. This is certainly of no small difficulty, but this does not defy hope.

4. Inquietude 2: Th in very metal-poor stars

The recent observations of r-nuclides, including Th, in the metal-poor halo stars CS 22892-052 or HD115444 (see C. Sneden and J.W. Truran, these Proceedings) have initiated a flurry of nucleo-cosmochronological excitement, both observationally and theoretically. The search for r-process-rich very low metallicity stars has been given an impressive boost. This is illustrated by the analysis of CS

31082-001. This star is the first one whose U content (not just an upper limit) has been measured (Cayrel et al. 2001). The abundances of other r-nuclides have also been measured in this same star (V. Hill et al., these Proceedings).

On the theoretical side, it is now commonplace to claim that an ideal nucleo-cosmochronometer has been found at last, the observed Th in the above-mentioned stars providing a clean way of measuring the ages of these stars, and consequently a reliable lower limit for the age of the Galaxy. In this concerted optimism, some individuals (among whom the authors of this contribution) dare expressing some reservation, however.

4.1. Is the r-process pattern 'universal'?

Almost all astrophysicists dealing with the Th data in very low-metallicity stars claim that the observed patterns of r-nuclide abundances are demonstrably solar, implying a 'universal' abundance distribution. This universality is of essential importance for bringing the observed Th to the status of a chronometer. It is clearly as essential not to take it too easily for granted!

Goriely & Arnould (1997) have tackled this question. They reach the conclusion that the CS 22892-052 r-process composition in the best observationally documented $56 \leq Z \leq 76$ range is remarkably close to the abundances obtained from a distribution that fits very nicely the *whole* solar distribution. However, they stress that it is very easy to construct 'artificial' r-nuclide distributions that reproduce almost equaly well the CS 22892-052 data in the Z range mentioned above, while they diverge substantially from the solar data outside of this range (including the actinides). Their so-called 'random distribution' even appears to reproduce relatively well (and by far better than the solar distribution) the observed $Z < 56$ abundance distribution.

From these results, Goriely & Arnould (1997) [see also Goriely & Clerbaux (1999)] conclude that *the convergence of the solar, CS 22892 - 052 and HD115444 abundance patterns in the* $56 \leq Z \leq 76$ *range does in no way demonstrate the universality of the r-process, without excluding it, however.* In fact, they stress that the r-pattern convergence is to a large extent the signature of the nuclear properties of the r-progenitors of the $56 \leq Z \leq 70$ elements, and does not provide any useful information on the stellar conditions under which the r-process may develop. This conclusion fully applies as well to the recent abundance determinations of $50 \leq Z \leq 70$ elements in 22 metal-poor r-process-rich stars (Johnson & Bolte 2001). In fact, only observations of $A = 90 - 130 - 195$ peak elements can shed light on astrophysics issues concerning the r-process.

In addition, there has been some bad news for the many proponents of the r-process universality with a report on the preliminary analysis of the very metal-poor halo star CS 31082 - 001, which shows large neutron-capture element enhancements comparable to the ones observed in CS 22892 - 052 (V. Hill et al., these Proceedings). While a large similarity between the $56 < Z < 70$ element patterns in CS 22892 - 052, HD115444 and CS 31082 - 001 is reported, the abundances in the latter star differ significantly from those of the other two stars in the $Z > 70$ range. This includes Th, the Th/Eu ratio in CS 31082 - 001 being 2.8 times larger than in CS 22892 - 052. Hence, under the universality assumption, CS 22892 - 052 (with [Fe/H]=-3.1) is older than CS 31082 - 001 (with [Fe/H]=-2.9) by 21 Gy and would be about 35 Gy old (see below). In

addition of smashing to bits the idea of the universality of the r-process which is so much beloved by some, the analysis of CS 31082 - 001 also reinforces our views that the question of the number of r-processes (two being these days in favor in a substantial part of the nuclear physics community) is of no substantial scientific interest. It would be more useful to unravel the basic mysteries of the r-process before trying to establish the number of r-process events!

4.2. And if the r-process were indeed universal, would it help much the Th chronometry?

From this point on, we will *assume* that the r-pattern of abundances is universal. To make things clear, this means nothing more and nothing less than the following: we assume that *all possible blends of 'r-process events' always lead to the same final abundance pattern*, an event being defined here, as in the canonical model of the r-process, by the ensemble (T, N_n, t_{irr}) of an assumed constant temperature and neutron concentration during the irradiation time t_{irr}. In direct relation with this statement, it may be worth making some remarks: (i) calling for a blend of r-process events is not at all equivalent to considering an ensemble of stars able to produce r-nuclides. As an example, a single supernova is most likely the site of some continuum of r-process events; (ii) the precise characteristics of the individual events which may contribute to the universal mix are unknown, as well as the relative level of the contribution of each of the events to the mix, and (iii) it cannot be excluded that different combinations of different individual r-events lead to the same final mix.[1]

Once the r-process universality is taken for granted, the procedure for estimating the age of the Th-bearing metal-poor stars is straightforward, at least in its principle. From the best possible fit to the solar system r-process abundance distribution, the Th r-process production Th_r can be deduced. The confrontation between this value and the observed abundances leads trivially to the stellar ages. Quite clearly, the consideration of very metal-poor stars allows to make the economy of a model for the chemical evolution of the Galaxy. This very nice feature is unfortunately compensated by the nightmare of evaluating Th_r with the high accuracy which is indispensable for building-up a chronometry.

As already mentioned in Sect. 2, the r-process remains the most complicated nucleosynthetic process to model from the astrophysics as well as nuclear physics point of view and is subject to large uncertainties that transpire directly into the Th_r predictions. The Th predictions are found to be especially sensitive to the nuclear mass evaluations. As shown by Goriely & Clerbaux (1999), different mass models lead to stellar age differences that can amount to more than 20 Gy for *r-process models fitting equally well the r-process data for CS 22892 - 052 and HD 115444 in the* $56 \leq Z \leq 82$ *range*. The reader may wonder why the quoted uncertainty is by far much larger than the one classically claimed in the literature. The reason may be summarized as follows: it is a common practice to identify the 'best' nuclear mass models from a confrontation between r-process predictions and the solar data (which are identical to the stellar ones through

[1] To make an analogy, it is well known in statistical mechanics that each macroscopic state of a complex gas system can be obtained through a variety of different superpositions of the states of the individual particles of the gas

the assumption of universality). This choice is biased, however. It results indeed from implicit assumptions that are made concerning the characteristic r-process events making up the universal mix. Other assumptions may lead to different best nuclear models. In other words, it is meaningless to select best mass models as long as the detailed characteristics of the suite of r-process events contributing to an assumed universal r-process pattern remain unknown.

This is indeed clearly the case as even the proper site(s) for the r-process is (are) not identified yet, all the proposed scenarios facing serious problems. The astrophysics uncertainty that most critically affect the reliability of the predictions of the Th production is clearly the still unknown maximum strength of the neutron irradiation that can be obtained in an r-process event. Age uncertainties amounting to about 16 Gy can result (Goriely & Clerbaux 1999).

Finally, one does not have to underestimate the uncertainties that still affect the evaluation of the contribution of the r-process to the solar-system Pb - Bi peak, the predicted Th abundance being directly correlated to this contribution. This situation is responsible for an uncertainty of about 20 Gy in the Th chronometry (Goriely & Clerbaux 1999).

As a conclusion, it is our opinion that the Th abundances observed in very low-metallicity stars are of no chronometric virtues even if the universality of the r-process is assumed, which is far from being demonstrated. As an example, uncertainties in the age of CS 22892 - 052 just originating from the errors in the Th abundance determination amounts to about 3.5 Gy. A comparable precision of theoretical origin would impose a 15 - 20 % level of accuracy in the r-process production of Th. This is just impossible to achieve! In fact, Goriely & Clerbaux (1999) report an age for CS 22892-052 lying in the $7 \lesssim T^*[\mathrm{Gyr}] \lesssim 39$ range! The many sources of uncertainties briefly mentioned above indeed blur the picture substantially, at least if no undue resort is made to too many 'toothfairies'.

5. Hope 2: Th/U in very metal-poor stars

As already stated elsewhere (Arnould & Takahashi 1999, Goriely & Clerbaux 1999), a way to rescue the Th chronometry discussed in Sect. 4 would be to have accurate measurements of the Th/U ratio in individual very low-metallicity stars. These nuclides are indeed likely to be produced concomitantly, so that one may hope to be able to predict their production ratios more accurately than the ratio of Th to any other r-element, in particular Eu.

A Th/U ratio has been reported recently for the star CS 31082 - 001 (Cayrel et al. 2001). This is real good news, even if the situation is not free of observational and theoretical difficulties. The former ones are discussed by Cayrel et al. (2001). On the theoretical side, one is still facing the severe question of the universality of the r-process (Sect. 4.1.). In addition, even if reduced, uncertainties remain in the evaluation of the Th/U production ratio. Goriely & Clerbaux (1999) estimate that it is likely to lie in the $1 \lesssim (\mathrm{Th/U})_r \lesssim 1.3$ range. This result, combined with the observed value $\log\epsilon(\mathrm{Th/U}) = 0.74 \pm 0.15$ leads to an age for the considered star of $14 \pm 3 \pm 2$ Gyr (where the errors correspond to observational and theoretical uncertainties, respectively).

Clearly, the Th/U chronometry based on data for individual very metal-poor stars has substantial potentialities which remain to be exploited. The

detection and analysis of other stars similar to CS 31082 - 001 would represent a major step forward in this direction.

6. Conclusion

Nucleo-cosmochronology has the virtue of always being able to provide numbers one can interpret as ages. The real challenge is to evaluate the reliability of these predictions. We estimate that the ^{187}Re - ^{187}Os will turn well as a chronometer based on meteoritic data. We are much more pessimistic concerning the classical ^{232}Th - ^{238}U and ^{235}U - ^{238}U pairs. On the other hand, we consider that it will remain close to impossible for long to date individual stars in a secure way without the help of precise determinations of the Th/U ratio in these stars.

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